sections of the country where tornadoes occur. The conditions that give rise to a northeastward movement can then be said to be normal. These normal conditions are an east to northeast movement of the LOW and a north to northeast drift of the winds within the LOW at the point where the tornado occurs, and the velocity of translation is the resultant of the velocities of these two components. After a study of weather maps and storm tracks, it seems that abnormal movements can be explained in this way.

For example, two tornadoes that have developed in West India hurricanes had abnormal movements. A tornado in Tallapoosa County on July 6, 1916, occurred when the hurricane was centered about 275 miles slightly south of east, near Vicksburg, Miss., and when the larger storm was on the recurve and moving northward. The surface wind at Montgomery was southeast, but the lower clouds were from the south; the tornado moved almost exactly north over a path 25 to 30 miles long.

The tornado that occurred 20 miles southwest of Miami, Fla., in the hurricane of September 10, 1919, and, as pointed out by Gray,[1] moved west-northwest with the strong southeast wind that prevailed at the time on the southeast Florida coast; the hurricane at the time was also moving west-northwest.

There is a tendency toward a more easterly movement of tornadoes in the southern part of the State than in the northern; this tendency is frequently noticeable on those occasions when tornadoes occur in northern and southern sections in connection with the same storm, and is probably due to the more easterly winds near the southern end of the LOW or trough. The easterly movements in the northern part of the State could be explained in a similar manner if the LOW were centered far to the north; and, in the cases investigated, this is true, the LOW sometimes being as far north as the upper Lake region. Occasionally northeasterly movements have been followed several hours later by easterly and southeasterly movements in the same general region; in these cases the LOW is found to have altered its course and dropped southeasterly from the Lake region to the middle Atlantic coast. Easterly or southeasterly movements would result if the axis of the LOW extended east and west, provided the tornadoes originated, as they usually do, in the southeastern quadrant of the cyclone, for then the winds would be westerly. An interesting and unusual case is pointed out by Williamson;[2] the tornado occurred in the southwestern quadrant of a LOW with major axis east to west and moved east to southeast, while the LOW was moving slightly north of east. An instance where the tornado originated in the northeast quadrant of the LOW and moved a little west of north is noted by Loveland.[3] The surface wind was southeast and the LOW was moving rather slowly northeastward. Tornadoes originating in the northeast quadrant are comparatively rare, apparently due to the contrary direction of the progressive motion of the LOW and the drift of the winds in that part of the LOW; since it is possible for the vertical temperature gradient to be as steep in the northeast as the southeast quadrant.

To show the relation of tornadoes in Alabama to the parent LOWS, monthly charts and a yearly chart were prepared showing the approximate location of the centers of the LOWS at the time the tornadoes occurred. On the monthly charts lines were drawn connecting the cyclonic

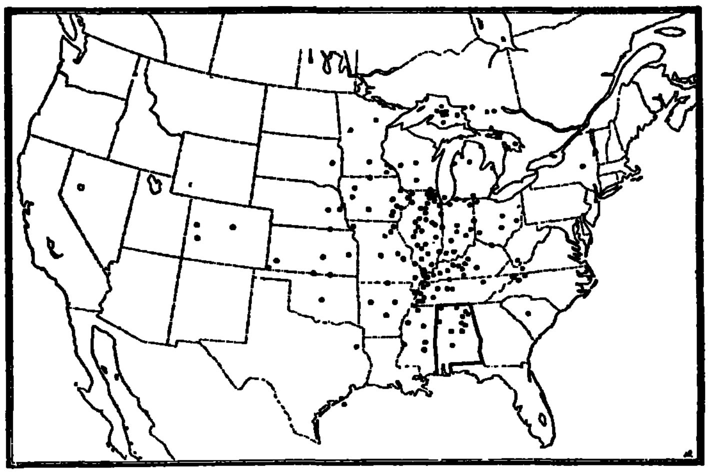

FIG. 6.—Location of the centers of LOWS which were accompanied by tornadoes in Alabama.

centers and the tornado tracks, but this was impracticable on the chart for the year. (Fig. 6.) Tracks of centers of cyclones in the MONTHLY WEATHER REVIEW since 1876 were used, the center, of the individual LOW being obtained from a consideration of its rate of movement. The charts show a wide divergence in the position of the centers, which is to be expected because of their varying size and shape. However, the most dangerous position for the center with respect to Alabama is 300 to 600 miles slightly west of north, more particularly in Illinois, Indiana, or western Kentucky and western Tennessee. Tornadoes occasionally occur when the center of the LOW is over the upper Lake region, but these are found to be greatly elongated, V-shaped LOWS.

[1] Gray, R. W. A Tornado within a hurricane area, MONTHLY WEATHER REVIEW, Sept., 1919, 47: 639.

[2] Williamson, R. M., Tornado in Davidson County, Tenn., May 12, 1923, MONTHLY WEATHER REVIEW, May, 1923, 51: 262.

[3] Loveland, G. A., Tornadoes in eastern Nebraska, April 6, 1919, MONTHLY WEATHER REVIEW, April, 1919, 47: 284.

THE PREDICTION OF MINIMUM TEMPERATURES FOR THE RED RIVER VALLEY

By ALBERT W. COOK

[Madison, Wis., August 19, 1925]

Damaging minimum temperatures have always been a matter of grave concern to the shipper of perishable goods, to the grower of citrus fruits in southern California and deciduous fruits in Washington and Oregon, to growers of cranberries in Wisconsin and New Jersey—in fact to all businesses dealing with commodities which suffer damage when exposed to low temperatures. And now, with the development of the potato industry and the advent of sugar beets to the Red River Valley the farmers of that section are confronted with the same problem, the protection of their produce while still in the field and unharvested. Before they will be willing to invest in expensive frost-fighting equipment, methods already in use elsewhere for accurately foretelling the occurrence of damaging minimum temperatures during the critical spring and autumn periods of plant growth must be adapted to the local atmospheric and topographic conditions under which frost occurs.

The general prediction of light, heavy, and killing frosts for considerable areas are made from the morning weather maps and are issued at the time of the regular morning forecast. These forecasts are usually quite accurate, but as they are made from 12 to 21 hours before the damaging temperatures occur and since unforeseen changes often come in the meantime, they are at times quite misleading.

Under these circumstances it becomes important that a definite statement of the expected minimum temperature be made. Such predictions should be made as early as possible, but from 6 to 12 hours warning would give ample time for the effective use of any method now in use on a commercial basis for protection against frost.

The purpose of this paper is to show the best method to be used at Grand Forks, North Dakota, for reducing the complex of meteorological factors involved in forecasting frosts, to simple, usable terms, whereby, from data available the day before, the ensuing minimum temperature may be forecast.

Grand Forks is located on the Red River of the North, about 835 feet above sea level, in latitude 47° 56′ N. and longitude 97° 2′ W. The topography of the surrounding territory is extremely level, being the bed of the former Lake Agassiz, which was a result of glacial action. Because of this levelness air drainage to valley floors is unknown. On the other hand, such atmospheric phenomena as mirage and looming are frequently observed. Moreover, it is not uncommon to see the smoke from large chimneys rise through stationary lower air to a height of 30 or 40 feet, and in some cases even higher, without the slightest sign of deflection and then turn at almost right angles to the rising column and blow out and diffuse. Conditions of level topography, absence of air drainage, and the marked division of air layers should make this locality, or any place in the Red River Valley, an ideal place to work with radiation and hygrometric relations in the prediction of minimum temperatures. Further, any method applicable at Grand Forks, should be applicable at any other place in the valley, using data appropriate to the latitude in each case.

Choosing of frost periods.—The first step was the determination, from climatological data,[1] of those periods during which frost is most apt to occur and the periods critical to crop growth in this locality.

It was found that the last killing frost in the spring has never occurred later than June 14, nor earlier than April 20, at Grand Forks. The critical period for the spring was therefore set from April 15 to June 15. In the fall the earliest occurrence of a killing frost was on August 20, and the latest on October 13. From these facts the critical period was set from August 15, to October 15.

From Weather Bureau records of the Grand Forks station covering these critical periods for the preceding five years, all nights when conditions were favorable for free radiation and frost were taken as a basis for the work, about 70 in the spring and an equal number in the fall. However, frosts severe enough to cause damage to plants were recorded only about one-fourth of the time when conditions for frost formation were favorable. Severe frosts occur about once in every 20 days during the critical periods.

Median-temperature hour method.—This method is based on the belief that the median or halfway temperature between the maximum of the day and the minimum of the following morning occurs at about the same time each day during clear, calm weather. Its application consists of determining the time of the median-temperature hour from a series of thermograph traces for past years. After this it becomes a simple matter to observe the temperature at that hour, subtract the observed reading from the maximum of the day, and then subtract this difference from the temperature observed at the median hour. The result is the ensuing minimum temperature. As an example: In April the median hour was found to be 9.17 p. m. The highest temperature for the day was 76° F. and at 9.17 it had fallen to 60° F.; the difference, 16°, subtracted from 60° leaves 44° as the expected minimum temperature for the following morning.

In testing the applicability of this method to Grand Forks, the time of the median hour for each month was found to be 9.17 p. m. for April; 10.25 p. m. for May; 9.48 p. m. for June; 9.53 p. m. for August; 8.54 p. m. for September, and 8.03 p. m. for October.

As a first check upon the method, the minimum temperature which would have been predicted by it was computed for all of the days under consideration, during the critical periods and comparisons then made with the observed minima. There were very few deviations of over 5°. Although it gives a fairly close check with the data from which it was calculated, it is more or less empirical. The real value, if any, will be shown in the practical application to new data.

Hygrometric relations.—The more important factors which determine the amount of drop in temperature during the night over a given locality are as follows: (1) Radiation of heat from the earth and the air and the temperature of the radiating surface; (2) importation of cold or warm air by winds and their effect in mixing the surface air so as to prevent temperature inversion; (3) the conditions of the sky; and (4) the local topography.

Thus we find that the factors responsible for the change in temperature may be any of, or a combination of, the following: Wind direction and velocity, humidity, dew point, clouds, temperature at the time of the observation, which for the purposes of this study will be taken as the temperature of the radiating surface, and the topography of the surroundings.

Although absolute calms are rare in this locality, the effect of the wind will be slight if the velocity is small, hence we may neglect this factor. Due to the level character of the land, factor five will not be considered. When conditions are favorable for free radiation the sky is clear and we may therefore neglect the third factor listed above.

The chief remaining factors are the radiation of heat, the temperature of the radiating surface, and some function of the humidity. But since the relative humidity and the dew point involve the air temperature at the time of the observation, we may drop the temperature of the radiating surface and thus finally leave humidity as the only factor to be considered, a factor which, presumably, exerts the greatest influence on decreases of temperature.

Since water vapor in the atmosphere is the most effective absorber of radiation from the earth, it follows that the amount of water vapor in the air above a given locality has considerable influence on the rate of fall of temperature at that place during nights when radiation conditions prevail. The temperature will fall more slowly when the moisture content is high than when it is low, other conditions being the same.

We may express the relation between relative humidity, dew point, and the expected minimum temperature, mathematically as follows:

$$\text{Minimum} = f\,(\text{dew point, relative humidity})$$

[1] Summary of climatological data for the United States, section 32; eastern North Dakota. Bulletin, Frost Data at Grand Forks, North Dakota, H. E. Simpson.

where f is some unknown function, which, if determined, will give an equation permitting the calculation of the minimum temperature.

The next step was to plot the depression of the minimum temperature below the evening dew point against the evening relative humidity. The arrangement of the dots on the plot approximated a straight line, tending to show a fairly close linear relation between the factors plotted.

To test this relationship the Pearsonian coefficient of correlation was computed and found to be -0.8243 ± 0.0249. The negative sign indicates that as the values of the relative humidity increase, the values of the depression of the minimum temperature must decrease. The value as found shows a high degree of correlation, in harmony with the approximately linear relationship shown by the plot.

To make the data of practical value the curve of "best fit" was computed by the method of least squares, and the constants of the linear equation, showing the

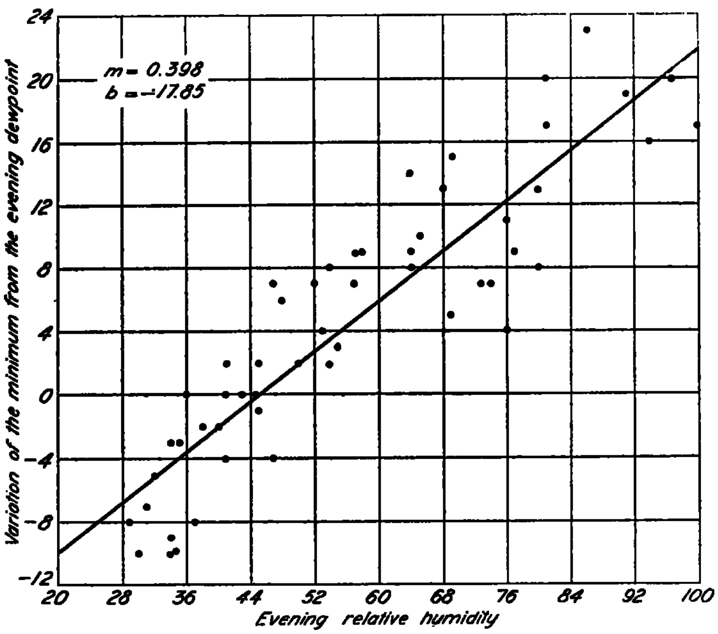

FIG. 1.—Relation between the evening relative humidity and the variation of the minimum from the dew point

relationship between the factors, were found. Using these constants and putting in the proper terms, our equation is:

$$Dp - Min = 0.398\ RH - 17.85,$$

or,

$$Min = -0.398\ RH + 17.85 + Dp$$

where Dp represents the dew point, RH the evening relative humidity and Min the expected minimum temperature. 0.398 is the slope of the line and -17.85 is the intercept on the y axis.

The distribution of the dots as plotted and the line given by the equation are shown in Figure 1, for the spring period.

The minimum temperature which would have been predicted by the method was computed for all days under consideration. In only two cases did it vary more than 6° from the actual recorded value.

Several direct methods were tried, such as plotting the minimum temperature against the relative humidity, and also against the depression of the wet bulb reading and the depression of the dew point below the evening dry temperature was plotted against the minimum temperature. The results were in no way indicative of of a close relationship. The dots were widely scattered and the correlation coefficient in all cases was below 0.5, which would indicate a nonlinear relationship.

In the consideration of the hygrometric data for the fall periods it was treated as a separate problem, but the same methods were used as for the spring period.

A dot chart was constructed, Figure 2, and the coefficient of correlation was computed as before and found to be -0.6 ± 0.091. Though not as high as the value for the spring, it is indicative of a linear relation.

The equation of the line of "best fit" may be expressed as follows:

$$Min = -0.2536\ RH + 10.96 + Dp$$

The estimated minimum which would have been predicted by the use of this formula did not vary more than 6° from the actual. This, like the formula for the spring period, gave a close enough check on back data to warrant further study. However, it can not be given

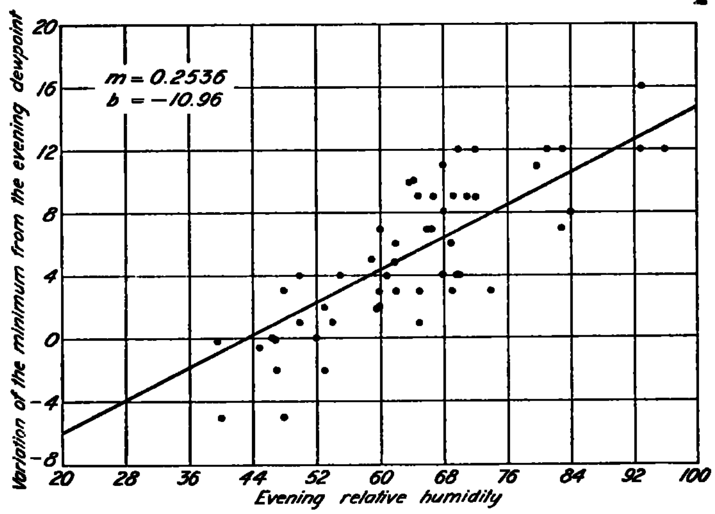

FIG. 2.—Relation of the evening relative humidity to the variation of the minimum from the dew point

much weight until we have further experimental evidence to show that it is satisfactory and usable.

Maximum-minimum temperature relations.—In the consideration of the median-hour method, it was shown that the halfway temperature between the maximum of one day and the minimum the following morning occurs at about the same time on days when the wind is light and the sky clear. If this is true, we should expect to find a direct relation between the maximum temperature to-day and the ensuing minimum temperature. The higher the maximum temperature to-day the higher should the minimum temperature be to-morrow morning, if conditions favoring active radiation prevail.

It follows, then, that the change in temperature between the maximum of the day and the minimum of the following morning is a function of the maximum and minimum temperatures. We may express this as follows:

$$\text{Change} = f\ (\text{maximum, minimum})$$

By plotting the maximum temperature against the minimum of the following morning we get an arrangement of dots, shown in Figure 3, for the spring and a similar arrangement for the fall. The coefficients of correlation were 0.8824 ± 0.0184 and 0.74 ± 0.080 for the spring and fall, respectively. These relatively high values gave sufficient proof of its approximation to a straight line to warrant the use of the data as plotted.

The next step was to compute the constants of the linear equation where

$$\text{Min} = m(\text{max}) + b$$

Min represents the expected minimum temperature, Max the maximum of the day, and m and b constants representing the slope of the line and the intercept on the y axis, respectively.

Substituting the values of m and b as found, we get

$$\text{Spring: Min} = 0.778 \text{ Max} - 13.58.$$

$$\text{Fall: Min} = 0.802 \text{ Max} - 13.50.$$

This formula is similar to the one used by Nichols at Grand Junction, Colo.[2]

This, like all of the other methods, gives a close check upon the data from which it was computed, but the practical tests on new data will give the real value of the equation.

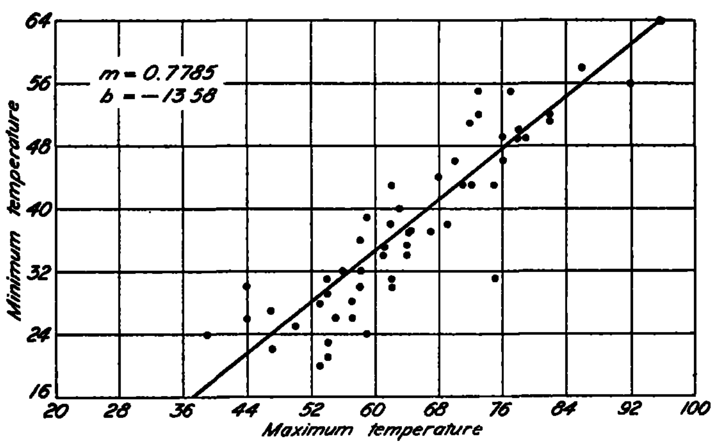

FIG. 3.—Relation between the maximum and minimum temperatures

Summary.—Frosts are most likely to occur on days when the weather control has passed to a high barometric area with its relatively clear skies and light winds. The prediction of damaging minimum temperatures during the critical periods in spring and fall is of vital importance to the agricultural interests of this vicinity.

After a careful examination of data for past years for days on which conditions were favorable for free radiation and frost, three methods for predicting the minimum temperatures which result in damage to crop growth were found applicable to Grand Forks. They are, first, the maximum-minimum temperature relation; second, the hygrometric-minimum temperature relation; and the median-temperature hour method.

In the first method a direct and approximately linear relation between the maximum of the day and the ensuing minimum temperature was found. The relation is expressed by a linear equation. By this method it is only necessary to observe the maximum as soon as it occurs in the afternoon, substitute its value in the formula and solve for the minimum temperature.

A direct relation between the humidity at the time of the evening observation (7 p. m. ninetieth meridian time) and the depression of the ensuing minimum temperature below the evening dew point was found. This also can be expressed as a linear equation.

Both formulas (spring and fall) gave a close check with the data from which they were computed.

[2] MONTHLY WEATHER REVIEW, Supplement 16.

The formulas were computed by working on the assumption that the moisture content of the air is the most effective agent in reducing the effect of radiation from the earth on clear, still nights.

The third method finds its application at a later hour than either of the above methods. The median hour varies from 8.05 p. m. to 10.25 p. m. as was shown in the discussion of the method. The use of this method was explained.

Application.—Beginning with March 31, 1924, the three methods of predicting the minimum temperature were used, on the basis of data available the day before and taken at the regular evening observation on all nights when conditions were favorable for free radiation. The following table shows the minimum temperature as given by each of the three different methods together with the variance of the estimated minimum temperature from the actual recorded value from March 31 to May 31, 1924.

TABLE 1.—*Comparison of the recorded minimum temperature with the minimum as estimated by each of the three methods, and the minimum temperature variance from each estimation for the spring season of 1924*

Date	Minimum	Hygrometric formula	Variation	Maximum-minimum formula	Variance	Median hour	Variance
March 31	16	16	0	15	−1	13	−3
April 1	25	24	−1	28	3	17	−8
2	31	31	0	35	4	18	−13
3	26	29	3	37	11	19	−7
5	27	22	−5	22	−5	22	−5
9	18	10	−8	14	−4	9	−9
11	14	9	−5	10	−4	10	−4
[a] 13	30	24	−6	22	−8	25	−5
17	28	23	−5	21	−7	24	−4
[a] 18	33	24	−9	21	−12	26	−7
19	23	23	0	25	2	22	−1
[a] 20	31	24	−7	21	−10	33	2
21	29	25	−4	23	−6	21	−8
[a] 22	30	38	8	35	5	38	8
[a] 23	47	39	−8	39	−8	46	1
24	36	32	−4	38	2	29	−7
29	30	27	−3	28	−2	30	0
30	31	34	3	32	1	32	1
May 1	31	31	0	29	−2	33	2
2	26	31	−5	31	5	26	0
3	25	27	−2	30	5	32	7
[a] 10	48	41	−7	39	−9	42	−6
11	44	47	3	43	−1	41	−3
[a] 12	30	20	−10	23	−7	21	−9
14	37	42	5	35	−2	40	3
15	46	47	1	48	2	39	−7
[a] 16	46	38	−8	38	−8	45	−1
17	31	28	−3	32	1	21	−10
18	24	25	1	22	−2	26	2
[a] 19	35	29	−6	28	−7	36	1
20	25	24	−1	26	1	25	0
22	31	33	2	32	1	31	0
23	28	23	−5	21	−7	25	−3
24	30	27	−3	26	−4	32	2
26	35	34	−1	38	3	33	−2
27	37	40	3	36	−1	36	−1
28	41	40	−1	38	−3	37	−4
29	34	34	0	35	1	44	10
30	35	35	0	37	2	35	0
31	39	43	4	42	3	40	1

[a] Indicates change of cloud conditions after prediction was made.

Omitting the cases where the temperature fall was influenced by cloud conditions, a condition purposely excluded in the development of the formula, and summarizing the table we get:

	Hygrometric formula	Maximum-minimum formula	Median-temperature hour method
	Nights	*Nights*	*Nights*
No variation	6	0	
Variation of 1°	6	8	
Variation of 2°	2	8	
Variation of 3°	7	4	4
Variation of 4°	3	4	3
Variation of 5°	6	3	1
Over 5°	1	4	10
	Per cent	*Per cent*	*Per cent*
Variation of 3° or less	67.7	64.5	58.1
Variation of 5° or less	97.5	87.1	64.5

It is readily to be seen that the values given by the hygrometric formula are the closest. In all cases where cloud conditions changed after the time of the observation the estimated minimum temperature varies more than 5°. If the evening weather map could have been used in conjunction with the formula the clouds could have been determined beforehand.

During the fall period there were 17 days when conditions were favorable for free radiation and frost. The two formulas gave the following results:

	Hygrometric formula	Maximum-minimum formula
	Nights	*Nights*
No variation	2	0
Variation of 1°	5	4
Variation of 2°	1	0
Variation of 3°	3	2
Variation of 4°	3	3
Variation of 5°	1	0
Over 5°	2	6
	Per cent	*Per cent*
Variation of 3° or less	64.7	35.3
Variation of 5° or less	88.2	64.7

The spring formulæ were used during the 1925 season with results as follows:

	Hygrometric formula	Maximum-minimum formula
	Nights	*Nights*
No Variation	3	2
Variation of 1°	1	5
Variation of 2°	4	4
Variation of 3°	6	1
Variation of 4°	2	1
Variation of 5°	3	2
Over 5°	2	6
	Per cent	*Per cent*
Variation of 3° or less	66.7	57.1
Variation of 5° or less	90.5	71.5

Conclusion.—The work described in this paper was of a preliminary nature, the data secured in one or two seasons being too meager to form the basis of any definite conclusions. However, the results obtained by using the two formulæ were of such a nature as to warrant further application and study. Use of the evening weather map is necessary in order to determine the cloud conditions in advance. Also, the probable influence of the wind in preventing stratification of the surface air could be determined from the evening map.

The formula alone can not be counted upon too strongly, but if used in conjunction with the evening weather map reliable predictions of the expected minimum temperature can be made.

The percentage of verification of forecasts from the maximum-minimum formula was not as high as that of the hygrometric formula, but was sufficiently high to justify its use in connection with the hygrometric formula and the weather map.

The median-temperature hour method did not give high enough verification to make its further use worth while.

All the formulæ used could be improved if applied consistently throughout the frost periods and as more data are secured.

A SHORT METHOD OF DETERMINING THE TIME OF MOONRISE AND MOONSET

By F. N. Hibbard

[Weather Bureau, Grand Haven, Mich., September, 1925]

The following notes and examples will be found useful to observers who find considerable labor and difficulty in computing moonrise and moonset.

Owing to the eastward motion of the moon in its orbit, it rises and sets on the average about 50 minutes later each day. Its velocity, however, is not uniform, nor is its path at a constant angle with the horizon, and the actual times of rising and setting are irregular, the lag varying from less than a half hour to considerably more than an hour.

The Weather Bureau has therefore furnished to each of its stations a nautical almanac and a set of auxiliary tables, the almanac being good for one year and the tables for many years. The almanac gives the risings and settings for various latitudes along the Greenwich meridian, and the tables give the corrections necessary to adapt the Greenwich figures to the Weather Bureau station.

To illustrate the use of the two, Table 1 gives the auxiliary figures as supplied to the Cincinnati station, and Table 2 shows how they are applied to the almanac figures.

Cincinnati lies between the latitudes of 35° and 40°. These two columns in the almanac will therefore be marked by heavy red or blue pencil (see columns a and b in Table 2). Cincinnati lies closer to the 40° latitude, therefore the corrections from the Auxiliary Table 1, A, will be applied to the 40° column (column b). These corrections are given in column c. Note that the corrections are plus when the figures in a are greater than those in b, and minus when less, Cincinnati lying between the two columns.

The results of the corrections are the main figures of column d. After the main figures are entered in pencil for the month, the differences (italic figures in column d) are entered in red ink. To the left of the differences the plus corrections from Auxiliary Table 1, B, are then entered in black ink (bold-face figures in column d), using the red figures for argument. Column e plus column f plus column g, the standard time correction, gives column h, the standard time of moonrise for the date and station. The standard time correction is plus when the station is west of its standard meridian, and minus when east.

Moonset is found in the same manner by using the moonset page in the almanac.

In actual practice the figures of column d only are set down, using the proper squares of Form 1078 for the purpose, the final figures, column h being entered directly in the daily local record, corrections c, f, and g being applied mentally. It is thus possible to list the essential figures, column d, for the entire year on two sheets of 1078, one for the moonrise and one for the moonset. And at no point in the operation has any figure been listed twice. The saving of time by this method is considerable.

In summarizing the operation, it may be helpful to know just where we are at the different points. Column a gives the time of moonrise on the Greenwich meridian for latitude 35°, and column b, for latitude 40; while column c gives the latitude correction. Column d gives